Preliminary study on the measurement of Higgs with CEPC

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On behalf of the CEPC collaboration

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Motivation

- The discovery of Higgs in 2012 is a milestone of particle physics.
- The further measurements of the properties of the particle confirm it is SM Higgs.
- The precision of Higgs measurement is important since the new physics (NP) could introduce a deviation ($\Delta \sim c v^2 / M_{NP}^2$) which is proportional to $1/M_{NP}^2$.
- With LHC, some systematics shows the bottleneck, e.g. theoretical sys. , for the precise measurements of the Higgs coupling etc...
- A lepton collider Higgs factory can provide a direct measurement of the Higgs xsection.
  - One of the proposals is the Circular Electron Positron Collider (CEPC).
At $e^+e^-$ collider, the dominant production is from HZ, the WW/ZZ fusions contribute a few percent of the total cross-section.

$e^+e^-$ collider provides a good opportunity to measure the bb, invisible decay of Higgs.

For 5 ab$^{-1}$ data with CEPC, 1M Higgs, 10M Z, 100M W are produced.
A CEPC (phase I)+ Super proton-proton Collider (SPPC) was proposed in IHEP, Sept. 2012

- Ecm \(\approx 240-250\) GeV, Lum 5 ab\(^{-1}\) for 10 years

An international linear detector (ILD) like detector is considered in the pre-CDR study.
Direct measurement of Higgs cross-section

\[ M_{\text{recoil}}^2 = (\sqrt{s} - E_{ff})^2 - p_{ff}^2 = s - 2E_{ff}\sqrt{s} + m_{ff}^2 \]

- For this model independent analysis, we reconstruct the recoil mass of Z without touching the other particles in an event.
- The \( M_{\text{recoil}} \) should exhibit a resonance peak at \( m_H \) for signal; Bkg is expected to smooth.
- The best resolution can be achieved from \( Z(\rightarrow e^+e^-, \mu^+\mu^-) \).
Direct measurement of Higgs cross-section

- ZZ, WW, Zγ and bhabha for Z→ll are dominant bkgs for Z→llH.
- For hadronic decay of Z, Z→qq and WW(qqqq,qqlv) are the most dominant bkgs as the right plot shows.
- The combined precision with three channels is $\Delta \sigma/\sigma = 0.5\%$.
Measurements of \((\sigma \cdot Br)/(\sigma \cdot Br)\) and \(\Delta Br/Br\)

1. A likelihood \(L(\Theta)\) is built:

\[
f(n_{cb}, a_p | \phi_p, \alpha_p, \gamma_b) = \prod_{c \in \text{channels}} \prod_{b \in \text{bins}} \text{Pois}(n_{cb} | \nu_{cb}) \cdot G(L_{0} | \lambda, \Delta L) \cdot \prod_{p \in \Sigma + \Gamma} f_p(a_p | \alpha_p)
\]

Shape info. for the discriminating Variables considered.

2. A profile likelihood ratio \(\lambda(\mu)\) (\(\mu\) signal strength in our case: \(\sigma \cdot Br\)) is constructed to estimate the parameters of interest:

\[
\lambda(\mu) = \frac{L(\mu, \hat{\Theta})}{L(\mu, \hat{\Theta})}
\]

\(0 \leq \lambda \leq 1\)

\(\mu\) is the test hypothesis (\(\mu=0,1\) correspond to bkg /signal+bkg only hypothesis)

3. If the likelihood ratio follows a \(\chi^2\) distribution, the significance can be approximately computed as \(\sqrt{\text{sqrt}[\text{-2*log}(\lambda)]}\) with \(\mu=1\);

Similarly, one can scan \(\mu\) (Minuit) and the error of \(\mu\) is the distance of x-axis between \(\mu=1\) and the point on the curve corresponding to \(-\log(\lambda)= 0.5\).

For the measurement of Br, the uncertainty from total xsection obtained from previous page is incorporated into the fit.
Measurement of Higgs width

- **Method 1**: Higgs width can be determined directly from the measurement of $\sigma(ZH)$ and Br. of $(H\rightarrow ZZ^*)$

  \[ \Gamma_H \propto \frac{\Gamma(H \rightarrow ZZ^*)}{\text{BR}(H \rightarrow ZZ^*)} \propto \frac{\sigma(ZH)}{\text{BR}(H \rightarrow ZZ^*)} \]

  - But the uncertainty of \text{Br}(H\rightarrow ZZ^*) is relatively high due to low statistics.

- **Method 2**: It can also be measured through:

  \[ \Gamma_H \propto \frac{\Gamma(H \rightarrow bb)}{\text{BR}(H \rightarrow bb)} \propto \frac{\sigma(\nu\bar{\nu}H \rightarrow \nu\bar{\nu}bb)}{\text{BR}(H \rightarrow bb)} \propto \Gamma(H \rightarrow WW^*) \cdot \text{BR}(H \rightarrow bb) = \Gamma(H \rightarrow bb) \cdot \text{BR}(H \rightarrow WW^*) \]

  \[ \Gamma_H \propto \frac{\Gamma(H \rightarrow bb)}{\text{BR}(H \rightarrow bb)} \propto \frac{\sigma(\nu\bar{\nu}H \rightarrow \nu\bar{\nu}bb)}{\text{BR}(H \rightarrow bb) \cdot \text{BR}(H \rightarrow WW^*)} \]

- These two orthogonal methods can be combined to reach the best precision.
Measurement of $\Delta(\sigma \cdot \text{Br})/(\sigma \cdot \text{Br})$ of ZH(jj)

For Z(\(\mu\mu\))H(bb), Z(\(\mu\mu\))H(cc), the recoil mass of Z is used as a discriminating variable to benefit from the good resolution of leptons.

Fast simulated samples are used in this study.

The combined precisions of for the measurement of H\(\rightarrow\)bb,cc,gg are 0.25%, 3.2%, 1.32% respectively.
Measurement of $\Delta(\sigma \cdot \text{Br})/(\sigma \cdot \text{Br})$ of ZH(WW)

This channel is necessary for the Higgs width measurement.

Leptonic and semi-leptonic decays of W bosons are used in the analyses.

MVA technique is implemented in the $Z\rightarrow(\ell\ell, ee)$ to further suppress ZZ bkg.

The combined precision is 1.5%.
Expected measured precision of $\sigma \cdot \text{Br}$ from other channels

4.3% including other processes (extrapolated from FCC-ee)

- $H \rightarrow ZZ$:
  - 6.9%

- $H \rightarrow \mu\mu$:
  - ~18%

- $ee \rightarrow \nu\nu H (\rightarrow bb)$:
  - 3.2%

- $H \rightarrow \gamma\gamma$:
  - 8.2% ($Z \rightarrow ll, \nu\nu, qq$ are 25.2%, 11.8%, 12.6%)

One way to Measure $\Gamma_H$
Measurement of the invisible decay of Higgs

- Invisible can be produced e.g. by the invisible decay of Higgs, NMSSM, 2HDM + singlet...
- For CEPC, the recoil mass method provides a chance to have the direct measurement.

Precision of invisible decay as a function of Br.
Measurement of the exotic decay of Higgs

• For the exotics searches, we tried semi-invisible, visible decays,
• one can achieve $9.4\sigma$, $8.43\sigma$ with $5 \text{ ab}^{-1} \text{ lum.}$, assuming the corresponding Br. of $H\rightarrow\chi_1\chi_2$ and $H\rightarrow hh\rightarrow 4b$ are 0.2%, 0.048% respectively.
Summary of the precision for the measurement of Higgs

<table>
<thead>
<tr>
<th>$\Delta M_H$</th>
<th>$\Gamma_H$</th>
<th>$\sigma(ZH)$</th>
<th>$\sigma(\nu\nu H) \times BR(H \rightarrow bb)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.5 MeV</td>
<td>2.7%</td>
<td>0.5%</td>
<td>2.8%</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Decay mode</th>
<th>$\sigma(ZH) \times BR$</th>
<th>BR</th>
</tr>
</thead>
<tbody>
<tr>
<td>$H \rightarrow bb$</td>
<td>0.25%</td>
<td>0.56%</td>
</tr>
<tr>
<td>$H \rightarrow cc$</td>
<td>3.2%</td>
<td>3.2%</td>
</tr>
<tr>
<td>$H \rightarrow gg$</td>
<td>1.3%</td>
<td>1.4%</td>
</tr>
<tr>
<td>$H \rightarrow \tau\tau$</td>
<td>1.2%</td>
<td>1.3%</td>
</tr>
<tr>
<td>$H \rightarrow WW$</td>
<td>1.5%</td>
<td>1.6%</td>
</tr>
<tr>
<td>$H \rightarrow ZZ$</td>
<td>4.3%</td>
<td>4.3%</td>
</tr>
<tr>
<td>$H \rightarrow \gamma\gamma$</td>
<td>8.2%</td>
<td>8.2%</td>
</tr>
<tr>
<td>$H \rightarrow \mu\mu$</td>
<td>22%</td>
<td>22%</td>
</tr>
<tr>
<td>$H \rightarrow inv$</td>
<td>0.28%</td>
<td>0.28%</td>
</tr>
</tbody>
</table>

- With combination of $\sigma=Br$ of $\nu\nu H(\rightarrow bb)/Br(H->bb)/Br(H->ww)$ and the direct measurement, one can obtain the decay width of Higgs with the precision at 2.7%.
- The measurement of Br is done by introducing the uncertainty of xsection of ZH from the direct measurement (no theoretical uncertainty needs to be taken into account).
- Most precisions are a few percent or lower (bb, invisible), allowing us to be sensitive to BSM deviation (Jianming’s talk yesterday).
- In comparison with HL-LHC, CEPC is expected to have much better performance in the measurements of the coupling constants in particular for $\kappa_z$. 

7-parameter fit
Conclusion

• A very preliminary study on the measurement of Higgs at CEPC has been done and is being documented in the Pre-CDR.

• As one e+e- collider, CEPC provides an exceptional opportunity to have a direct measurement of Higgs cross-section with a precision at \( \sim 0.5\% \) for 5 ab\(^{-1}\) data.

• The recoil mass method by reconstructing only the Z boson also provides the best probe into H->invisible decays and search for dark matter and exotics produced in the Higgs decays.

• CEPC can measure the Higgs decays and couplings with precisions at a few percent or sub-percent level, (e.g. \( h\rightarrow bb \) at 0.56\% for Br measurement), sensitive enough to some new physics deviation.
Backup Slides
Why an $e^+e^-$ Higgs factory

$$g/g_{SM} \sim 1 + \delta(1\text{TeV}/\Lambda_{NP})^2$$

<table>
<thead>
<tr>
<th>NP model</th>
<th>$\delta(hVV)$</th>
<th>$\delta(htt)$</th>
<th>$\delta(hbb)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Extra Higgs</td>
<td>$&lt;1%$</td>
<td>$&lt;1%$</td>
<td>$1.7%$</td>
</tr>
<tr>
<td>Composite Higgs</td>
<td>$8%$</td>
<td>$\sim 10%$</td>
<td>$\sim 10%$</td>
</tr>
<tr>
<td>Mixed in Singlet</td>
<td>$6%$</td>
<td>$6%$</td>
<td>$6%$</td>
</tr>
<tr>
<td>MSSM</td>
<td>$&lt;1%$</td>
<td>$3%$</td>
<td>$10%-100%$</td>
</tr>
<tr>
<td>Top parter</td>
<td>$0.8 \text{–} 2.9%$</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

...Higgs couplings: **absolute** measurements to percentage level...
... a vision of New Physics Landscape at TeV era...
Measurement of $\Delta(\sigma \cdot \text{Br})/(\sigma \cdot \text{Br})$ of $ZH(jj)$

Table 7. Expected event yields for signal and backgrounds for $ZH$ production with $H \rightarrow bb/cc/gg$, normalized to 5 ab$^{-1}$. The signal efficiency as well as the expected precision of the measurement ($\Delta(\sigma \times \text{BR})/\sigma \times \text{BR}$) is also shown.

<table>
<thead>
<tr>
<th>Channel</th>
<th>$H \rightarrow bb$</th>
<th>$H \rightarrow cc$</th>
<th>$H \rightarrow gg$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Z \rightarrow \mu\mu$</td>
<td>signal/efficiency</td>
<td>10773/52.8%</td>
<td>283/31.2%</td>
</tr>
<tr>
<td></td>
<td>background</td>
<td>469</td>
<td>441</td>
</tr>
<tr>
<td></td>
<td>$\Delta(\sigma \times \text{BR})/\sigma \times \text{BR}$</td>
<td>0.98%</td>
<td>9.5%</td>
</tr>
<tr>
<td>$Z \rightarrow ee$</td>
<td>signal</td>
<td>10853/49.4%</td>
<td>319/30.9%</td>
</tr>
<tr>
<td></td>
<td>background</td>
<td>723</td>
<td>685</td>
</tr>
<tr>
<td></td>
<td>$\Delta(\sigma \times \text{BR})/\sigma \times \text{BR}$</td>
<td>0.99%</td>
<td>9.9%</td>
</tr>
<tr>
<td>$Z \rightarrow qq$</td>
<td>signal</td>
<td>148749/35.9%</td>
<td>3887/20.4%</td>
</tr>
<tr>
<td></td>
<td>background</td>
<td>7584</td>
<td>17219</td>
</tr>
<tr>
<td></td>
<td>$\Delta(\sigma \times \text{BR})/\sigma \times \text{BR}$</td>
<td>0.27%</td>
<td>3.7%</td>
</tr>
<tr>
<td>Combined</td>
<td>$\Delta(\sigma \times \text{BR})/\sigma \times \text{BR}$</td>
<td>0.25%</td>
<td>3.2%</td>
</tr>
</tbody>
</table>